Ultra-small RFID p-Chips on the heads of entomological pins provide an automatic and durable means to track and label insect specimens

Article *in* Zootaxa · June 2012

DOI: 10.11646/zootaxa.3359.1.3

CITATIONS
7

READS
1,711

10 authors, including:

Garry Jolley-Rogers
The Commonwealth Scientific and Industrial Research Organisation
31 PUBLICATIONS **279** CITATIONS
SEE PROFILE

David K Yeates
The Commonwealth Scientific and Industrial Research Organisation
339 PUBLICATIONS **11,221** CITATIONS
SEE PROFILE

Edith Margaret Cawsey
The Commonwealth Scientific and Industrial Research Organisation
20 PUBLICATIONS **564** CITATIONS
SEE PROFILE

Phillip John Suter
La Trobe University
86 PUBLICATIONS **1,080** CITATIONS
SEE PROFILE

Zootaxa 3359: 31–42 (2012)
www.mapress.com/zootaxa/

Article

ISSN 1175-5326 (print edition)
ZOOTAXA
ISSN 1175-5334 (online edition)

Ultra-small RFID p-Chips on the heads of entomological pins provide an automatic and durable means to track and label insect specimens

G. JOLLEY-ROGERS[1], D.K. YEATES[2], J. CROFT[1], E. M. CAWSEY[3], P. SUTER[4], J. WEBB[4], R.G. MORRIS[5], Z. QIAN[5], E. RODRIGUEZ[5] & W. MANDECKI[5]

[1]*Taxonomic Research and Information Network (TRIN), P.O. Box 1700 Canberra ACT 2601, Australia. E-mail: Garry.Jolley-Rogers@csiro.au; Jim.Croft@environment.gov.au*

[2]*Australian National Insect Collection (ANIC), CSIRO, Canberra ACT 2601, Australia. E-mail David.Yeates@csiro.au*

[3]*Australian National Wildlife Collection (ANWC), CSIRO, Canberra ACT 2601, Australia. E-mail Margaret.Cawsey@csiro.au*

[4]*Department of Environmental Management and Ecology, La Trobe University, Australia. E-mail P.Suter@latrobe.edu.au; jmw975@yahoo.com*

[5]*PharmaSeq, Inc., 11 Deer Park Drive, Suite 104, Monmouth Junction, NJ 08852, USA. E-mail rmorris@pharmaseq.com; qian@pharmaseq.com; mandecki@pharmaseq.com; rodriguez@pharmaseq.com*

Abstract

A new, ultra-small, light-activated microtransponder ("p-Chip") has been integrated into the heads of entomological pins to improve efficiency in collections management and research through radio frequency identification (RFID) of insect specimens. These specimens are typically small, fragile, numerous and especially difficult to track. Globally, the majority are not currently recorded in any database. The application of unique identifiers has previously proven time consuming and difficult. Permanent and integral to the specimen, each p-Chip transmits a unique serial number allowing tracking without contact and reducing the risk of damage to specimens and repetitive strain injuries (RSI) in curators. The p-Chips and the specimens they tag can be linked immediately to biodiversity web services and collections databases. Specimens can be rapidly assigned to groupings as they are sorted and their taxonomic identity refined; and accurately tracked through high throughput methods and analyses. Quite importantly, with the p-Chips, the profile of the pin head is unchanged, and there is no discernible tactile difference from standard entomological pins. We also describe how p-Chips can be retro-fitted to provide complete compendia of legacy samples.

Key words: Automation, management, collections, barcode, tracking, label, taxonomy, radio frequency identification

Introduction

Efficient maintenance and development of biological collections relies on the ability to quickly and accurately label and track specimens. This is especially so in disciplines that are fundamentally concerned with observations of occurrence, number, diversity and relationship such as taxonomy, systematics and ecology. So far, tractable machine readable methods for rapid and reliable tracking of entomological specimens have proven elusive. Here we describe how ultra-small RFID transponders may be integrated unobtrusively, without risk of damage to newly pinned or existing entomological specimens. We report very rapid *in situ* acquisition of specimen identifiers in a form that facilitates data linkage and automation.

Insects form the greatest proportion of the 2.5–3.0 billion biological specimens in the world's natural history collections (OECD, 1999), predominantly in the form of dried specimens on entomological pins (Vollmar et al., 2010). These pinned specimens and their associated metadata are the primary reference points (vouchers) for insect taxonomy and, as such, represent a global resource for understanding the identities and distributions of insects (Grytnes & Romdal, 2008). They also form an essential reference resource for high priority research, e.g. in agriculture, food security, disease control, climate change and the environment (Merriman, 2008; Pinto et al., 2010; Shaffer et al., 1998; Suarez & Tsutsui, 2004). Limited access to specimen information constrains productivity in these and other like fields. It limits the capacity to collect and collate information about insect taxa from collections

Accepted by Z.-Q. Zhang: 18 Apr. 2012; published: 28 Jun. 2012

and the productivity of emerging research based on techniques such as genetic barcoding and environmental genomics which are data intensive and require high volumes of rapidly collected samples (La Salle et al., 2009; Patterson et al., 2010; Thessen & Patterson, 2011; Vollmar et al., 2010). Consequently, the digitisation of specimen information is an international priority and a central agenda for programmes such as the U.S. National Science Foundation's *Advancing Digitization of Biological Collections Program* (NSF, 2011) and *The Atlas of Living Australia* (ALA, 2011).

Only a small fraction of the data associated with entomological specimens has been entered into databases and less still is available in a form that can be exchanged digitally for further analysis. Fewer than 5% of all botanical and zoological specimens in collections are recorded in the Global Biodiversity Information Facility (GBIF) (Beaman et al., 2006; GBIF, 2011). In part, this is due to the expense of manual entry of specimen label data that may be detailed, idiosyncratic and terse (GBIF, 2008; Heidorn & Wei, 2008). Progress has been made in the extraction of information from labels which can be easily scanned such as plant specimen labels (Heidorn & Wei, 2008). However, in order to meet constraints on space, entomological specimens often employ non-standard shorthand and abbreviations. Further, specimens are typically not recorded in a ledger or database and many collections do not assign accession numbers to individual specimens (Vollmar et al., 2010). Many such specimens are known only to their curators, if they are known at all.

All identification and labelling systems for entomological collections face common constraints (Riley, 1892; Upton & Mantle, 2010; Walker & Crosby, 1988). Specimens are stored at high densities on 38 mm entomological pins. Once mounted, pins effectively become part of the specimen; they are rarely removed without risk of damage. They are grouped and sorted taxonomically in cabinet drawers lined with cushioning materials such as polystyrene foam (Styrofoam) or cork, or, increasingly, in standard 'unit trays' (typically 36 mm deep x 90 mm wide and up to 225 mm long) lined with such materials and arranged in cabinet drawers. Hundreds of fragile specimens may be stored in a given unit tray. Specimens range in size from less than a millimetre to several centimetres. They are vulnerable to damage whenever they are examined or handled. Labels must be sufficiently small that they do not touch adjacent specimens and so damage delicate articulations such as limbs, antennae, sensory hairs, scales and wings, which are important for identification and research into biology, reproduction and behaviour. Visibility must be maintained so that the specimens can be examined unimpeded, e.g. paper labels are generally placed underneath specimens (Figure 1). Finally, labelling systems must be of archival quality; persistent, readable for centuries, and resistant to pests, the long term processes of decay (e.g. verdigris) and the preservatives used to prevent it (Story, 1985).

In current practice, dried entomological specimens carry paper tags which can range in size from circa 6 x 6 mm to circa 18 x 6 mm; on which may be recorded accession details, determinations of taxonomic identity and any other pertinent annotations. With tiny tags comes brevity especially when large numbers of specimens need to be accessioned. In many collections, catalogue numbers may not be assigned and identification may be only at the level or taxonomic order or family and this essential information on tags may date rapidly. There is limited provision for amendment or addition of new information as the taxonomic identity of the specimen is refined. It is not uncommon to see many tags stacked underneath high-value specimens; each conveying fragmentary information or sometimes catalogue numbers (or barcodes) from several collections. The application of each of these tags requires time and skill that are a premium in budget constrained collections. The number of tags on a specimen often correlates with the utilisation (and thus, in part, the value) of a specimen in research and the frequency a given specimen is handled.

Barcodes are widely used in herbaria and museums to label large, non-entomological, specimens (Russell, 1999; Rácz & Gannon, 2005). They have proven especially useful in circumstances where a specimen needs to be accessed repeatedly e.g. as part of a series of assays and for lineage tracking of samples (Thomas & Schotz, 2011). To date, the deployment of barcodes in entomological collections has been on a small scale and opportunistic. Some collections use barcodes designed to fit onto standard entomology tags and barcode readers have been correspondingly adapted (Johnson, 2009). The Museum of Comparative Zoology, Harvard University, mounts labels with barcodes facing downwards so they may be read without moving labels or the specimen (Morris et al., 2010). Furthermore, the written or printed labels are invariably retained alongside the barcodes to provide a failsafe and longevity. Barcode systems are still being developed and their use of barcodes in museums has not been standardized. Several propriety and open source barcode systems are in common use (Rácz & Gannon, 2005; USDA, 2011).

The addition of barcodes to entomological specimens can be physically challenging, requiring curatorial expertise, so retrospective barcoding of specimens occurs infrequently and incidentally. There is always a risk of damage posed by additional handling (Vollmar et al., 2010) whenever a label is added or manipulated for reading, as may be necessary when there are many stacked labels under the specimen. Institution specific barcodes may be added when a specimen is lent to a collection that barcodes new accessions (Mantle 2011, pers. comm.) or when a valuable specimen, such as a type, is re-examined as a target of a study (Morris et al., 2010).

FIGURE 1. Examples of how labels may be stacked below entomological specimens. Important information may be hidden and difficult to access.

Small radio transponders, such as passive radio frequency identification (RFID) tags, have been used for wireless identification of all manner of objects. An RFID tag typically consists of electronic circuitry and a solenoid antenna mounted on plastic, paper or enclosed in a glass capsule. The transponders transmit unique alphanumeric codes that are easily distinguished from each other by a dedicated reading device. Such tags have been deployed on a very large scale in applications ranging from inventory and supply chain management and health care, to the identification of live animals, public transport, access control and service provision (ticketing) (Curtin et al., 2007). Typically, transponders are approximately the size of a postage stamp, including the aerial. They are inexpensive and easy to deploy. When activated, they broadcast the identity of the object in a manner that can be integrated with mobile databases and software to realise the potential of "*integrated, ubiquitous, pervasive computing*" as conceived by Gold et al. (1999) and Roussos & Kostakos (2009), i.e. where data-enabled devices sense objects and respond in context *in situ*. Interactions between instrumented objects, specimens or animals can trigger sensors, processing and data capture (Philipose et al., 2004; Satyanarayanan, 2001). In this manner, some of the smallest

available RFID tags have been deployed to track the behaviour of small vertebrates (Andrews, 2004; Charney, et al, 2009; Frick, 2010) and large, strong insects (Moreau et al., 2010; Sumner et al., 2007).

Entomological specimens are not well suited for tagging with standard RFID chips. Specimens are stored in high densities in steel cabinets and small specimen size places unrealisable limits on aerial design. High RFID transponder densities also present difficulties in response "*conflict resolution*" due to the challenge of separating simultaneous responses from RFID tags (Roussos & Kostakos, 2009). The smallest conventional flat RFID tags are is around 20 × 30 mm (AVID, 2011; Alien Technology, 2007). Smaller RFID tags (6 × 1 mm) have been designed for insertion into laboratory animals such as mice and come in a capsule-like form (Kent Scientific, 2011; Nonatec, 2011). These are too large to fit onto the head or the shaft of an entomology pin.

p-Chips have no external antenna, and so can be an order of magnitude smaller than other currently available transponders (PharmaSeq, 2011). Developed for biomedical applications for DNA and cell assays (Lin et al., 2007; Mandecki et al., 2006), they are stable and robust. They have been used to tag and track small laboratory animals by subcutaneous injection (Gruda et al., 2010) and to track the identity and weight of live ants, *Temnothorax albipennis* (Robinson et al., 2009a; Robinson et al., 2009b; Robinson et al., 2008). p-Chips consist solely of a 500 µm by 500 µm by 100 µm integrated circuit (weighing ~85 µg) composed of photocells, clock signal extraction circuits, a logical state machine, and a loop antenna. Current pChips have a *"write once read many times"* 30-bit memory which can hold over 1.1 billion possible identification codes. This would increase circa 7 x 10^{28} possible codes should storage be increased to 96 bits as planned (PharmaSeq, 2011). p-Chips are manufactured on silicon wafers in commercial silicon foundries, using standard CMOS fabrication techniques commonly used in the manufacturing of memory chips and computer processors. Wafers receive post-fabrication treatment consisting of: laser encoding, passivation, thinning and dicing to yield individual p-Chips. The p-Chip surface is made of silicon nitride, which is deposited as a final passivation layer and provides an abrasion-resistant outer coating. p-Chips are selectively activated by a focussed laser beam, and thus are not subject to response conflicts that occur when radio powered transponders are deployed at high densities. They are stable under challenging circumstances such as prolonged extremes in temperatures (-196 to 520ºC), microwaves, autoclaving and are resistant to most chemical reagents. When illuminated by a pulsed laser beam, the photocells efficiently power the electronic circuits on the chip harvesting around ~10% of beam energy. The response is transmitted by modulated current in the antenna (Figure 2) to produce a varying magnetic field that is received by a pickup coil in a reader, analysed and decoded. All information related to the tagged specimen is contained in a secure database indexed by the p-Chip identifiers.

Here we describe how p-Chips may be incorporated unobtrusively into the heads of entomological pins allowing seamless, real-time connection between the physical specimens, data- enabled devices, databases and the World Wide Web. Entomological pins are integral to the specimen from the time it is chosen and mounted, so the association of specimens and transponders is effectively permanent. We present a design that allows retrospective labelling of existing samples with minimum disruption and risk of damage. We report on the *in situ* performance of p-Chip augmented pins as specimen tags and the resilience of these tags to some physico-chemical circumstances and challenges common to entomological collections and research practice. Finally, we describe how automated identity acquisition can bring efficiencies to entomological collection management and research.

Materials and evaluation

p-chips

p-Chips were obtained from PharmaSeq, Inc. (Monmouth Junction, New Jersey) who produced them from their proprietary design at a commercial semiconductor foundry. Eight inch wafers were passivated with silicon dioxide and silicon nitride, thinned to 100 µm, and diced into the final product using standard techniques employed in the semiconductor industry.

ID readers and software

A purpose built ID Reader ("wand"), designed and supplied by PharmaSeq, was used to read the p-Chip IDs (Figure 2). Under typical conditions, serial numbers can be acquired in much less than a 0.5 seconds at a distance of 0.5 cm from an unmounted p-Chip. The wand consists of a diode laser (660 nm, 60 mW average power), a magnetic pickup coil and associated electronics, all powered by a laptop computer via a USB cable. p-Chips were acti-

vated by line-of-sight illumination from the laser that provided power via the p-Chip's photocells for the response. Pre-programmed serial numbers were transmitted at 1MHz through a variable magnetic field that is created by modulated current from the antenna fabricated on the chip itself. This signal was picked up by a coil in the wand, and decoded using a field programmable gate array (FPGA) that is integral to the wand itself, and software (PharmaSeq) running on a standard PC under Microsoft Windows. Serial numbers were recorded as time and data stamped events in a comma separated text file for subsequent analysis.

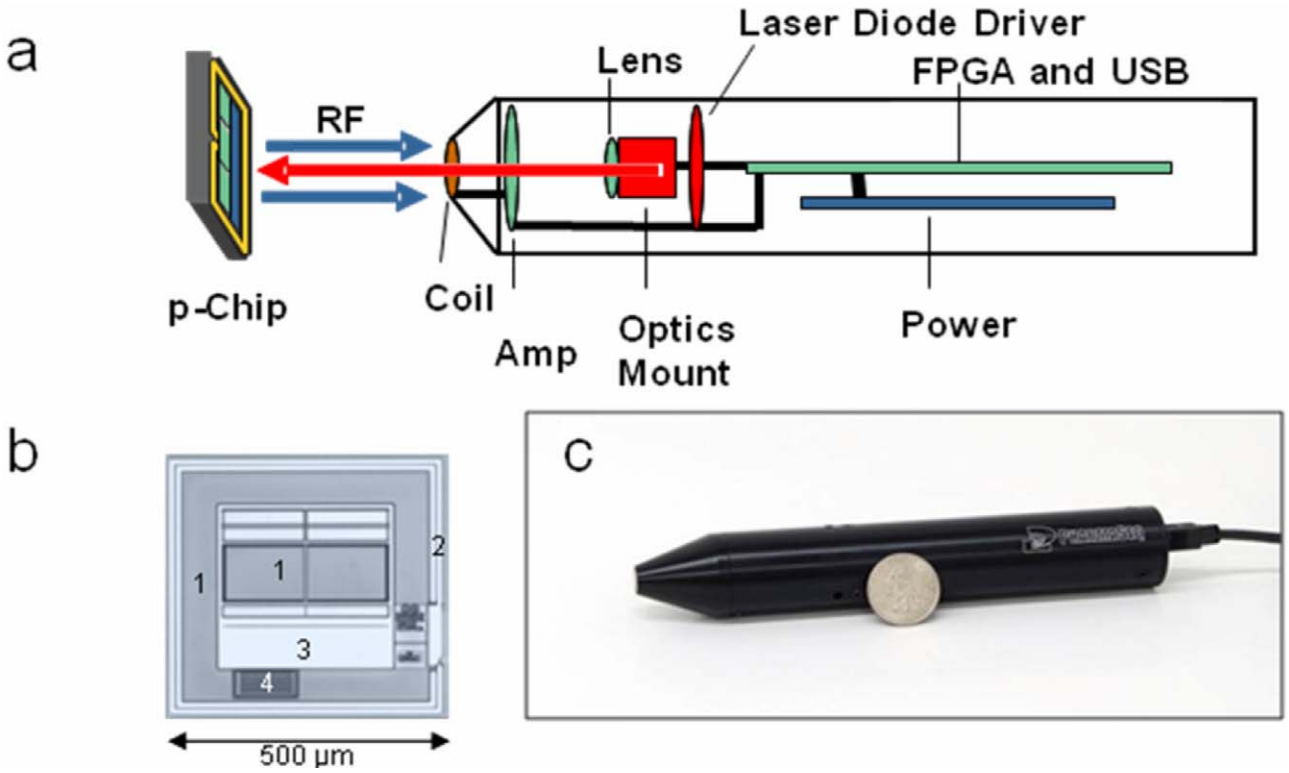

FIGURE 2. a) Schematic of the wand design and interactions with a p-Chip; b) Photograph of the p-Chip. Key elements labelled include: 1. Photocells, 2. Antenna, 3. Logic circuits, 4. Memory. c) Photograph of the wand used to read p-Chip IDs. The wand is next to a U.S. quarter coin for size comparison.

Preparation of new entomological pins

A schematic view of the modified pin head is shown in Figure 3. Three gauges of commercially available 38mm insect pins were obtained from BioQuip (2011). The p-Chips measured 500 µm by 500 µm by 100 µm and fit comfortably onto the BioQuip No. 2 or No. 3 pin (Table 1). There was minimal variability in the diameter of pin heads (e.g. for five No. 2 entomological pins the mean diameter was 1143 µm, with $\sigma = 0.02$ µm). The surface of the pin head was ground flat using a sanding cutter (Craftsman model 572.530320). The chip was positioned in the centre of the flattened surface of the head and attached with circa 2–5 nL of high performance metal binding epoxy adhesive, Scotch-Weld DP-100 Plus Clear, resistant to solvents such as acetone and ethanol (3M, 2009). The assembly was examined under a microscope and the adhesive left to cure for 30 minutes. To prevent scratches and damage to the face of the p-Chip and facilitate subsequent handling by technicians, a second larger amount of the same adhesive (100–300 nL) was applied as a sealant and left to cure for a further 30 minutes. The embedded p-Chips (Figure 3) were tested for correct functionality 24 hours later.

TABLE 1. Types of insect pins used.

		Diameter of		
BioQuip pin no.	Length (mm)	Shaft (µm)	Entire head (µm)	Flat surface on top of head (µm)
1	38	250	762	710
2	38	450	1143	740
3	38	500	1320	740

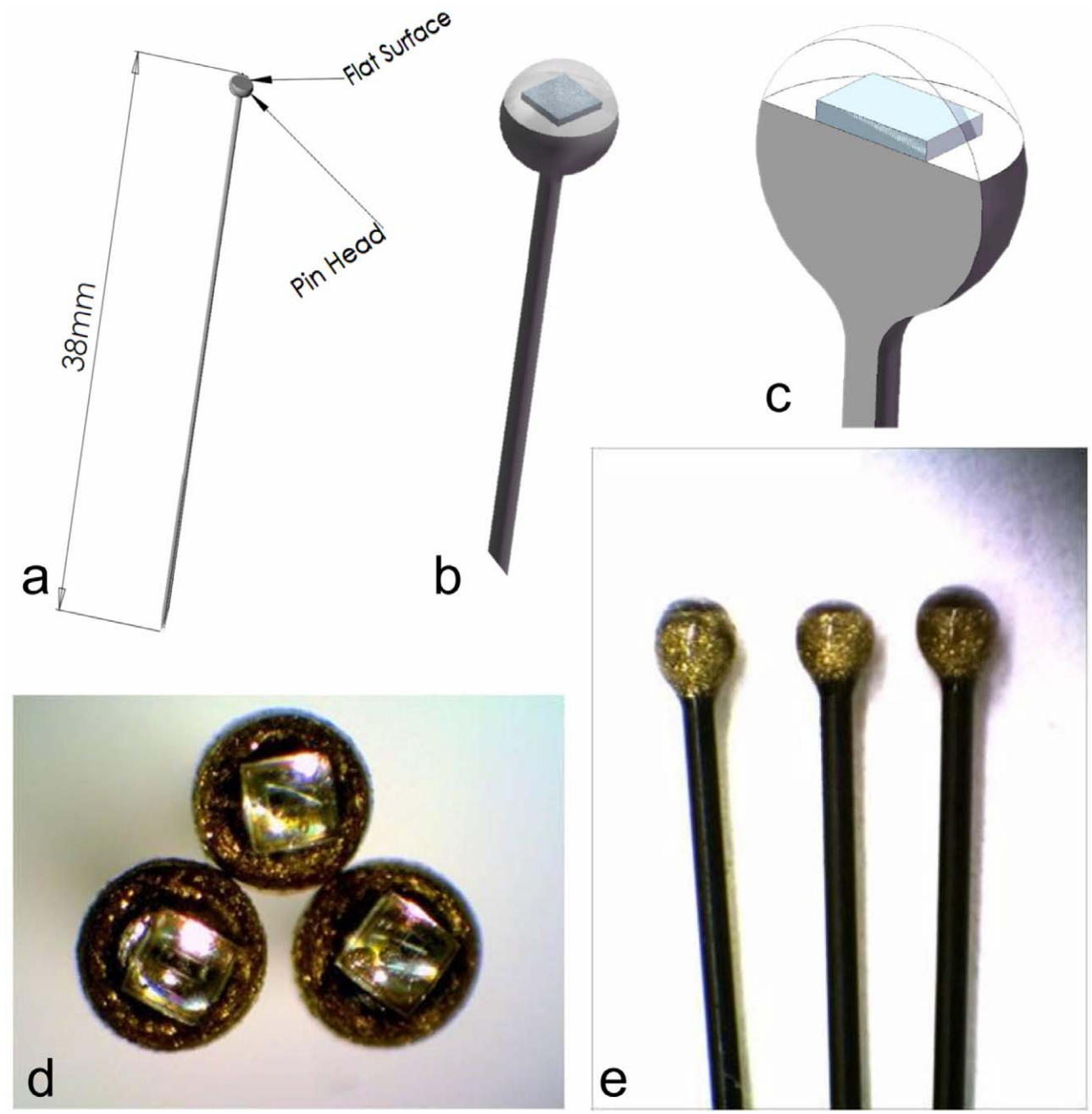

FIGURE 3. a)-c) Schematic representation of p-Chips embedded in an epoxy dome and mounted onto entomological pins. d)-e) Photographs of p-Chip-tagged pins; a view from above the pin head (d), and from the side (e).

Attachment to existing specimens

The p-Chip can be fitted as a cylindrical 'cap' to an existing pin, without associated specimen (Figure 4). The largest component of the cap was made from Vero photopolymer resin using stereolithography (3D printing) by PCS Engineering, Inc. (Timonium, MD, USA). Ferrite was added to amplify the strength of the magnetic field generated by the p-Chip. To assemble the cap, a cylindrical piece of ferrite was positioned in the centre of the flat top of the cap and glued with 2–5 nL of high performance binding epoxy adhesive, Scotch-Weld DP-100. Then, a p-Chip was positioned in the centre of the top, flattened surface of the ferrite cylinder with the same adhesive, which was left to cure for 30 min. To prevent scratches and damage to the face of the p-Chip and facilitate subsequent handling by technicians, a second larger amount of the same adhesive (100–300 nL) was applied as a sealant and left to cure for a further 30 min. The embedded p-Chips were tested 24 hours later. To apply the cap to a pin, the

inside of the cap was filled with the Scotch-Weld DP-100 Plus Clear epoxy glue, and the cap was pressed over the head of the pin. A small quantity of glue was sufficient to secure a pin head to the cavity. The cap was left undisturbed on the specimen for 30 minutes to allow the glue to cure. No direct handling of the specimen was required to fit the cap.

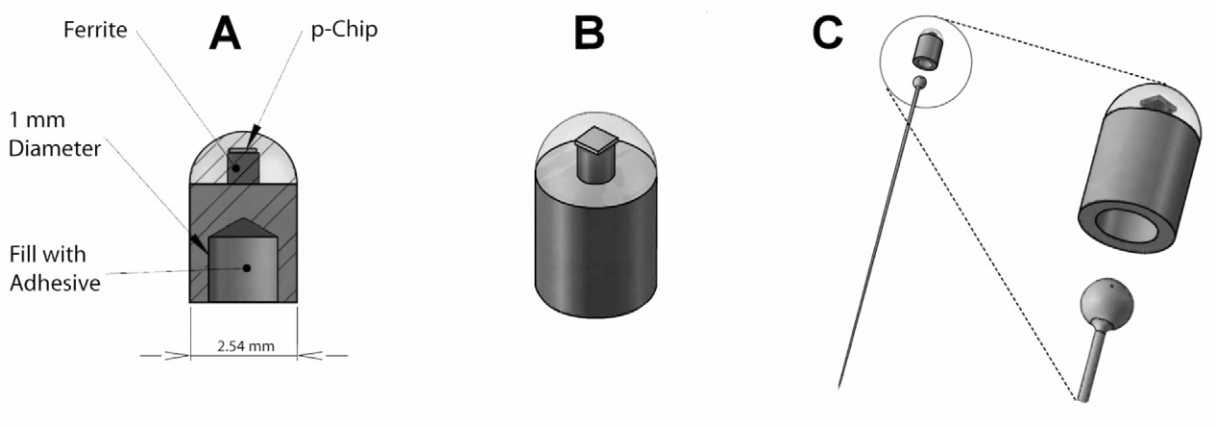

FIGURE 4. Schematic of a cap for tagging specimen-bearing pins with p-Chips attached to a piece of ferrite to amplify the transponder response. A: Cross-section; B: Overall view; C: Mounting of the cap on a pin.

Tactile discrimination

Ten technical scientific staff recruited from the Centre for Australian National Biodiversity Research were each presented with eight entomological pins in a standard entomological unit tray (measuring 55 by 90 mm). Half of the pins had p-Chips mounted directly onto the pin head as described above. Participants were not informed about any differences in the sample pins; they did not know that p-Chip existed. They were asked to sort pins into two groups by touch alone; those that felt 'different' or 'the same'. Participants were free to take as much time as desired and to select pins in any order but not to look at the pins.

Pins with transponders were equally likely to be placed in either the 'same' or 'different' group ($p >> 0.10$, $n = 10$ Student's t-test). Two of the participants, one with expertise in taxonomy and one with expertise in needlework, could reliably sort pins with chips from those without. Other participants could not discern the presence of p-Chips. Overall, the likelihood of pins with p-Chips being judged the same as other entomological pins was significantly higher than would be expected if p-Chips could be reliably detected by touch alone ($p < 0.05$, $n = 10$, Student's t-test).

***In Situ* speed tests**

Eighteen pins with p-Chips mounted were set up in a regular array in a standard entomological unit tray (measuring 55 by 90 mm). Four participants (all authors on this paper: JRC; EMC, GJR, DY) used the wand supplied by PharmaSeq to read accession numbers from transponders mounted in the heads of entomology pins. The serial number and time of reading was recorded using the standard software supplied by the manufacturer. Participants were free to target pins in the order that best suited them and to hold and manipulate the unit tray in a natural manner.

Accession numbers could be easily read from all p-Chip tested. Mean read times for chip recorded for five trials for each participant as follows: JRC $\mu = 1.1$ seconds / pin $\sigma = 0.3$ seconds; EMC $\mu = 1.3$ seconds / pin $\sigma = 0.5$ seconds; GJR $\mu = 1.3$ seconds / pin $\sigma = 0.7$ seconds; DY $\mu = 1.0$ seconds / pin $\sigma = 0.1$ seconds.

Resilience to common chemical agents

Pins with p-Chips mounted were immersed for 14 days in one of five sealed vials. Three pins were placed in each vial. Each vial contained one of five chemical reagents including i) 100% Tea Tree oil, ii) a 10% aqueous solution of potassium hydroxide (KOH), iii) a 70% aqueous solution of ethanol, iv) a commercial product based on Orange Oil, *OrangePower* (Austech Products, 2011) and v) 100% acetone. These reagents are commonly used in entomology collections and we believed that they represented likely challenges for the glue and circuitry of the transponder. Tea tree oil and Oil of Cajaput contain an especially rich mix of terpenes, most notably terpinene-4-ol. They are used in entomological collections as antimicrobial and antifungal agents. Strongly basic and hygroscopic,

potassium hydroxide is used for the removal of soft tissues from exo- and endo-skeletons (e.g. Paul, 1981). Ethanol and acetone are ubiquitous fixatives / preservatives for soft tissue and solvents (Pantin, 1964). Orange oil contains high concentrations of d-limene, a common solvent and clearing agent used as an alternative to xylene (Buesa & Peshkov, 2009).

Vials were inspected at 1, 7 and 14 days immersion in each reagent. Immersion for one day in 10 % KOH sufficed to detach all three chips from pins with no readable signal from chips. All chips in the other four reagents, i.e. Tea Tree Oil, ethanol, Orange Oil, and acetone, remained attached to pins after 14 days immersion with no diminution in the speed with which transponders could be read (Table 2).

TABLE 2. Results of 14-day immersion tests of p-Chip pins (n=3 for each agent) with chemical agents commonly used in Collections.

Agent	Active ingredient	p-Chip still attached to pin	p-Chip active
Tea Tree oil 100%	terpinene-4-ol	3	3
Potassium hydroxide	KOH 10%	0	0
OrangePower	d-limonene ~5%	3	3
Ethanol	ETOH 70%	3	3
Acetone	$(CH_3)_2CO$ 100%	3	3

Discussion

Here we report on a means to actively and wirelessly label and track small pinned insect specimens with no discernable tactile change in physical outline of the head of the pin. On activation, these p-Chips transmit a unique identifier by which specimens can be linked automatically to databases or data enabled devices. The p-Chips are robust and long-lived. Integrated into the pin, they become an intrinsic part of the specimen. In the short to medium term, the use of these transponders can improve productivity in curation and research. Unlike barcodes, specimens have unique identifiers as soon as they are selected and pinned. Opportunities to collect and collate information are maximized. Many collections currently assign accession identifiers in batches after specimen preparation. In contrast, p-Chips provide a means of rapidly collating subsequent observations which can be placed in context through online databases which report occurrences and holdings in international collections (ALA, 2011; Global Biodiversity Information Facility, 2011; Johnson, 2007) to relevant knowledge that is tied to current or past taxonomic ideas (Johnson, 2007; NSL, 2011; Patterson et al., 2010) and to emerging online resources for the identification of species/taxa (Identify Life, 2011).

pChip identifiers can be configured to be unique for entomological collections worldwide. They could also identify the institution which accessioned the specimen through either i) the inclusion of a dedicated (high-order) bit code or ii) or segmentation of the address space so that given ranges of identifiers correspond to particular institutions. Alternatively, pChip identifiers could remain abstract, globally unique specimen based code as envisaged by Page (2008) which could be used as a key into online databases held by international registries such as GBIF. In which case, a suitably formed URL which included the pChip identifier would return information about the specimen such as where it is held, taxonomic determinations, derived samples, measurements, sequences and associated metadata.

The cost of the p-Chip-tagged entomological pin will be a small fraction of the total cost of curation for a given specimen. There are potential savings in data entry costs and error reduction that may become significant on a large scale. Similarly, an automated facility to rapidly track specimens will reduce the cost of large scale, high-throughput, intensive research methods. The cost of silicon manufacturing of the p-Chip on silicon wafers is currently on the order of few cents per chip. Even if wafer processing costs and costs to embed the p-Chip on the pin are added, it is clear that in large-scale manufacturing the price of the p-Chip-tagged pin will be affordable. Similarly, as the complexity of the PharmaSeq wand can be compared with that of a cell phone, it is expected that the wand manufacturing costs can be reduced to the level of that of a smart cell phone if the volume is sufficiently large.

As with all automated labelling systems, including barcodes, there is a risk that appropriate readers and supporting technology may not be available on the time scales which apply in museums (decades to centuries). The electronic components that make up the ID reader are conventional, commercial-off-the-shelf items and are quite

ordinarily available, and are anticipated to be so for decades to come. There is no reason why wands or wand type devices could not be built well into the future as the design does not rely upon rare or uncommon elements. Specimen accession numbers could also be printed on *MicroDots* that can be read with a hand lens or microscope (Whitehead & Peakall, 2011). These could be attached to specimens to provide a visual supplement to remote identification via p-Chip transponder. However, we believe paper labels will always be required to ensure continuity of specimen information - independent of databases. Indeed, p-Chips could also be embedded within labels.

We subjected the p-Chip-tagged pins to a range of physical and chemical challenges commonly found in entomological collections. p-Chips proved resilient to commonly used solvents, fixatives, and preservatives with the exception of potassium hydroxide (a search is ongoing for glues that can survive in strong alkalic solution and have archival properties). In all other cases, p-Chips remained functional and in place on the pin after 14 days immersion. Glues also can be a source of volatiles, some which are of concern to curators (Down et al., 1996). Given the small quantity of the glue used (< 5 nL), it is unlikely there will be a detectable release of volatiles from the glue. There is minimal risk to the conservation of specimens. Properly handled and encapsulated, p-Chips can be expected to last centuries. In entomological collections, stresses on the circuitry would be very much less than operational limits with no known wearout mechanisms present. Identifiers are non-volatile, encoded into the chips during fabrication. They are permanent and secure.

This technology will reduce risk of damage to specimens through handling. As with barcodes on labels, p-Chips can be used to automate the acquisition of specimen accession numbers and details without the need to handle the specimens, as identifiers can be read at a distance. Unlike barcoded labels, specimens do not need to be handled for the ferrite cap based transponder to be fitted. In entomological collections, manual handling of pins by technicians and scientists is also a significant source of occupational (workplace) related injuries, precisely because of the dexterity required in repetitive tasks. The incorporation of p-Chips will not impact negatively upon workplace practices in entomology but rather increase the potential for improvement. In trials we found that pins with p-Chips could not be discerned by touch alone by non-experts. Only participants with experience in very fine tactile discrimination could reliably detect mounted p-Chips by touch.

After a very small amount of practice, we found that accession numbers could be reliably read from an array in a standard '*unit tray*' of 18 entomological pins in 20–25 seconds. PharmaSeq has recently made refinements to the wand that increases the distance at which p-Chip identity can be read. We expect this will make targeting of individual pins easier and further improve the speed at which pin identity can be read *in situ*.

Deployed on a large scale, p-Chips could allow tools and practices of inventory management refined in commerce (Curtin et al., 2007) to be applied to museum and entomological collections to track around 1.1 billion specimens with the current capacity of 30-bit encoded identifiers. Further increases of the p-Chip memory size are anticipated. Pharmaseq plans to expand pChip memory to 96 bits of electronic antifuse memory providing 7×10^{28} possible identifiers. The current estimated holdings of all natural history collections, 4.2 billion specimens (OECD, 1999), could be encoded in 32 bits. It is likely that many institutions may not be able to fund the fitting of p-Chips to millions of specimens. However, there are advantages in small scale and more targeted use of these devices. Notable thefts of biological material holdings from museums (e.g. ICAC, 2003) have led to requests from insurers for periodic audits to confirm that institutions still hold select valuable specimens (Cremers, 2006; Wilson, 2010). p-Chips allow for quick verification of holdings with no visual impact on specimens. Elsewhere, the p-Chips have been used to tag and track small laboratory animals, ranging from mice and rats to bees (Gruda et al., 2010), and to integrate the analysis of ant behaviour with instrumentation. Similarly, these p-Chips can be used to streamline intensive, process driven research such as the automated extraction and documentation of specimen characters (La Salle et al., 2009), reduce the need for handling especially for high value specimens or those which are the object of intensive process driven research resources such as the barcode of life (Hebert & Gregory, 2005), or as a tool for quality control for environmental surveys which allows initial determinations of taxonomic identity to be rapidly recorded and subsequently verified (New, 1996).

The use of these or similar unobtrusive, long lived devices to provide automatic labelling and tracking of specimens will assist in the rapid refinement of taxonomic concepts which fundamentally rely on examination and cataloguing of variation between specimens (Bolton, 2007; Johnson, 2007). And further, that wireless, active labelling and tracking will enable collections-based entomology to contribute more effectively to data-centric *'Big Biology'* initiatives in biodiversity, evolution and conservation research (Drew, 2011; Graham et al., 2004; Johnson, 2007; Philippi & Köhler, 2006; Thessen & Patterson, 2011).

Acknowledgements

This research was funded in part by the Australian Commonwealth Environmental Research Facilities (CERF) Fund. We wish to thank Beth Mantle, Cate Lemann, Ainsley Seago and Kimberi Pullen from The Australian National Insect Collection for generous help and fearless comments. We also wish to thank Judy West and volunteers from staff of The Centre for Australian National Biodiversity Research.

References

3M. (2009) Scotch-Weld DP 100 Plus Clear Technical Data. Available from http://www.3M.com/industrial (May 30, 2011)

ALA. (2011) The Atlas of Living Australia. Available from http://www.ala.org.au/about/program-of-projects/ (May 30, 2011)

AVID. (2011) Avid Technologies. Available from http://www.avid-tech.com/ (May 31, 2011).

Alien Technology. (2007) *"Tag Feng Shui": A Practical Guide to Selecting and Applying RFID Tags Followers of the ancient Chinese practice of Feng Shui*. http://www.alientechnology.com/docs/WP_Alien_Tag.pdf (May 31, 2011).

Andrews, K.M. (2004) PIT Tagging: Simple Technology at Its Best. *BioScience*, 54(5), 447–454.

Austech Products. (2011) Material safety data sheet: Orange Power Carpet & Upholstery Spot Cleaner. Available from http://www.orangepower.com.au/ (December 12, 2011).

Beaman, R., Macklin, J., Donoghue, M. & Hanken, J. (2006) Overcoming the Digitization Bottleneck in Natural History Collections: A summary report on a workshop held 7-9 September 2006 at Harvard University. Available from http://bdei2.cs.umb.edu/wiki/images/b/b3/Harvard_data_capture_wkshp_rpt_2006.pdf (February 9, 2012).

BioQuip. (2011) Lab equipment and Supplies. Available from http://www.bioquip.com/html/view_catalog.asp?page=32 (June 2, 2011).

Bolton, B. (2007) How to conduct large-scale taxonomic revisions in formicidae. In R.R. Snelling, B.L. Fisher, & P.S. Ward (Eds.), *Advances in ant Systematics (Hymenoptera: Formicidae); homage to E. O. Wilson - 50 years of contributions. Memoirs of the American Entomological Institure, 80.* (pp. 52–71).

Buesa, R.J., & Peshkov, M.V. (2009) Histology without xylene. *Annals of diagnostic pathology*, 13(4), 246–56.

Charney, N.D., Letcher, B.H., Haro, A. & Warren, P.S. (2009). Terrestrial Passive Integrated Transponder Antennae for Tracking Small Animal Movements. *Journal of Wildlife Management*, 73(7), 1245–1250.

Cremers, T. (2006) Theft, the Internet and Museum Objects : Threats and Opportunities. *International Council of Museums News*, *59*(4), 4.

Curtin, J., Kauffman, R.J., & Riggins, F.J. (2007) Making the "MOST" out of RFID technology: a research agenda for the study of the adoption, usage and impact of RFID. *Information Technology and Management*, 8(2), 87–110.

Down, J.L., MacDonald, M.A., Tétreault, J., & Williams, R.S. (1996) Adhesive testing at the Canadian Conservation Institute: An evaluation of selected poly (vinyl acetate) and acrylic adhesives. *Studies in Conservation*, 41(1), 19–44.

Drew, J. (2011) The Role of Natural History Institutions and Bioinformatics in Conservation Biology. *Conservation Biology*, 25(6), 1250–1252.

Frick, M.G. (2010) Misconceptions about the ability of researchers to relocate the holotype of the Galapagos pink land iguana through the use of a passive integrated transponder. *Zootaxa*, 2694, 57–58.

Global Biodiversity Information Facility. (2008) *GBIF Training Manual 1: Digitisation of Natural History Collections Data, version 1.0.Natural History.* Copenhagen: Global Biodiversity Information Facility.

Global Biodiversity Information Facility. (2011) Global Biodiversity Information Repository Portal. Available from http://data.gbif.org/welcome.htm (May 27, 2011).

Gold, R., Brown, J.S., Sprague, B. & Bruce, R. (1999) The origins of research at PARC. *IBM Systems Journal*, *38*(4), 693–696.

Graham, C.H., Ferrier, S., Huettman, F., Moritz, C. & Peterson, A.T. (2004) New developments in museum-based informatics and applications in biodiversity analysis. *Trends in Ecology & Evolution*, 19(9), 497–503.

Gruda, M.C., Pinto, A., Craelius, A., Davidowitz, H., Kopacka, W.M., Li, J., Qian, J., Rodriguez, E, Kuspiel, E. & Mandecki, W. (2010) A system for implanting laboratory mice with light-activated microtransponders. *Journal of the American Association for Laboratory Animal Science*, 49(6), 826–31.

Grytnes, J.-A., & Romdal, T.S. (2008) Using Museum Collections to Estimate Diversity Patterns along Geographical Gradients. *Folia Geobotanica*, 43(3), 357–369.

Hebert, P.D.N., & Gregory, T.R. (2005) The promise of DNA barcoding for taxonomy. *Systematic Biology*, 54(5), 852–9.

Heidorn, P.B., & Wei, Q. (2008) Automatic metadata extraction from museum specimen labels. *Proceedings of the 2008 International Conference on Dublin Core and Metadata Applications* (pp. 57–68). Dublin Core Metadata Initiative.

Identify Life. (2011) Identify Life. Available from http://www.identifylife.org/ (November 9, 2011).

Independent Commission Against Corruption New South Wales. (2003) Australian Museum - theft of zoological specimens (Operation Savoy). Available from http://www.icac.nsw.gov.au/investigations/past-investigations/investigationdetail/7 (June 15, 2011).

Johnson, N.F. (2007) Biodiversity informatics. *Annual review of entomology*, 52, 421–38.
Johnson, N.F. (2009) Chapter 18. In R.G. Foottit & P.H. Adler (Eds.), *Insect Biodiversity Informatics: Science and Society* (pp. 433–443). Wiley-Blackwell.
Kent Scientific. (2011) RFID Transponder System. Available from http://www.kentscientific.com/products/productView.asp?ProductId=6239 (May 31, 2011).
La Salle, J., Wheeler, Q., Jackway, P., Winterton, S., Hobern, D. & Lovell, D. (2009) Accelerating taxonomic discovery through automated character extraction. *Zootaxa*, 2217, 43–55.
Mandecki, W., Ardelt, B., Coradetti, T., Davidowitz, H., Flint, J.A., Huang, Z., Kopacka, W.M., Lin X., Wang Z. & Darzynkiewicz, Z. (2006) Microtransponders , the Miniature RFID Electronic Chips, as Platforms for Cell Growth in Cytotoxicity Assays. *Cytometry Part A*, 69A, 1097–1105.
Merriman, N. (2008) Museum collections and sustainability. *Cultural Trends*, 17(1), 3–21.
Moreau, M., Arrufat, P., Latil, G., & Jeanson, R. (2010) Use of radio-tagging to map spatial organization and social interactions in insects. *Journal of Experimental Biology*, 214(1), 17–21.
Morris, P.J., Eastwood, R., Ford, L.S., Haley, B. & Pierce, N.E. (2010) Innovative Workflows for Efficient Data Capture in an Entomological Collection : The MCZ Rhopalocera (Lepidoptera) Rapid Data Capture Project. *Entomological Collections Network*.
NSL. (2011) Australian National Species Lists. Available from http://www.ala.org.au/about/program-of-projects/names-services/ (November 9, 2011).
National Science Foundation. (2011) Advancing Digitization of Biological Collections (ADBC). Available from http://www.nsf.gov/pubs/2010/nsf10603/nsf10603.htm (May 30, 2011).
New, T.R. (1996) Taxonomic Focus and Quality Control in Insect Surveys for Biodiversity Conservation. *Australian Journal of Entomology*, 35, 97–106.
Nonatec. (2011) Identification and traceability solutions. Available from http://www.nonatec.net/know-how.html (May 31, 2011).
OECD. (1999) *Final Report of the megascience forum working group on biological informatics*. (pp. 1–74). Paris: OECD.
Page, R.D.M. (2008) Biodiversity informatics: the challenge of linking data and the role of shared identifiers. *Briefings in bioinformatics*, 9(5), 345–54.
Pantin, C.F.A. (1964) *Notes on Microscopical Technique for Zoologists*. Cambridge University Press.
Patterson, D.J, Cooper, J., Kirk, P.M.M., Pyle, R.L.L., & Remsen, D.P.P. (2010) Names are key to the big new biology. *Trends in Ecology & Evolution*, 25(12), 686–91.
Paul, D.H. (1981) Homologies between neuromuscular systems serving different functions in two decapods of different families. *Journal of Experimental Biology*, 94, 169–187.
PharmaSeq. (2011) RFID. from http://www.pharmaseq.com/pages/rfid.html (May 31, 2011).
Philipose, M., Fishkin, K.P., Perkowitz, M., Patterson, D.J., Fox, D., Kautz, H. & Hahnel, D. (2004) Inferring Activities from Interactions with Objects. *IEEE Pervasive Computing*, 3(4), 50–57.
Philippi, S. & Köhler, J. (2006) Addressing the problems with life-science databases for traditional uses and systems biology. *Nature reviews. Genetics*, 7(6), 482–8.
Pinto, C.M., Baxter, B.D., Hanson, J.D., Mendez-Harclerode, F.M., Suchecki, J.R., Grijalva, M.J., Fulhorst, C.F. & Bradley, R.D. (2010) Using museum collections to detect pathogens. *Emerging infectious diseases*, 16(2), 356–7.
Riley, C. V. (1892) Directions for Collecting and Preserving Insects. *Nature*, 46(1192), 416–416.
Robinson, Elva J.H, Feinerman, O. & Franks, N.R. (2009) Flexible task allocation and the organization of work in ants. *Proceedings of the Royal Society Series B*, 276, 4373–4380.
Robinson, Elva J.H, Smith, F. D., Sullivan, K.M.E. & Franks, N.R. (2009) Do ants make direct comparisons? *Proceedings of the Royal Society Series B*, 276, 2635–2641
Robinson, Elva J.H., Richardson, T.O., Sendova-Franks, A.B., Feinerman, O. & Franks, N.R. (2008) Radio tagging reveals the roles of corpulence, experience and social information in ant decision making. *Behavioral Ecology and Sociobiology*, 63(5), 627–636.
Roussos, G. & Kostakos, V. (2009) RFID in pervasive computing: State-of-the-art and outlook. *Pervasive and Mobile Computing*, 5(1), 110–131.
Russell, G. (1999) An overview of bar code applications and issues in systematics collections. *In*: D.A. Metsger & S.V. Byers (Eds.), M*anaging the Modern herbarium: An interdisciplinary approach* (pp. 253-261). Washington, D. C.: Society for the Preservation of Natural History Collections.
Rácz, G.R. & Gannon, W.L. (2005) Improving Collection Maintenance Through Innovation: Bar-Code Labeling to Track Specimens in the Processing Stream. *Collections; a Journal for Museum and Archive Professionals*, 1(3), 227–242. Collections.
Satyanarayanan, M. (2001) Pervasive computing: vision and challenges. *IEEE Personal Communications*, 8(4), 10–17.
Shaffer, H.B., Fisher, R.N. & Davidson, C. (1998) The role of natural history collections in documenting species declines. *Trends in Ecology & Evolution*, 13(1), 27–30.
Story, K.O. (1985) *Approaches to pest management in museums*. Conservation Analytical Laboratory, Smithsonian Institution.
Suarez, A.V., & Tzutsui, N.D. (2004) The Value of Museum Collections for Research and Society. *BioScience*, 54(1), 66–74.
Sumner, S., Lucas, E., Barker, J. & Isaac, N. (2007) Radio-tagging technology reveals extreme nest-drifting behavior in a euso-

cial insect. *Current Biology*, 17(2), 140–5.
Thessen, A.E. & Patterson, D.J. (2011) Data Issues in the Life Sciences [White Paper]. Available from http://dataconservancy.org/sites/default/files/Data Issues in the Life Sciences White Paper.pdf (February 9th 2012)
Thomas, M.A. & Schotz, E.-M. (2011) SAPling: a Scan-Add-Print barcoding database system to label and track asexual organisms. *Journal of Experimental Biology*, 214(21), 3518–3523.
United States Department of Agriculture. (2011) Collecting and Preserving Insects and Mites: Tools and Techniques. Available from http://www.ars.usda.gov/Main/site_main.htm?docid=10141&page=10 (May 31, 2011).
Upton, M.S. & Mantle, B.L. (2010) *Methods for collecting, preserving and studying insects and other terrestrial arthropods.* (5th ed.). The Australian Entomological Society Miscellaneous Publication No. 3.
Vollmar, A., Macklin, J.A. & Ford, L. (2010) Natural history specimen digitization: challenges and concerns. *Biodiversity Informatics*, *7*(2), 93–112.
Walker, A. & Crosby, T. (1988) *The Preparation and curation of insects*. *Entomology Division, Department of Scientific and Industrial Research, New Zealand*. Auckland, New Zealand: Department of Scientific and Industrial Research.
Whitehead, M.R. & Peakall, R. (2011) Microdot technology for individual marking of small arthropods. *Agricultural and Forest Entomology, 13*(5). doi:10.1111/j.1461-9563.2011.00556.x
Wilson, A. (2010) Auditor-General claims museum's $ 750m collection is 'out of control '. *The Australian,* 2nd September 2010